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Tannins as antimicrobial agents: Understanding toxic effects on pathogens

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ABSTRACT

"Tannins" are compounds that belong to a group of secondary metabolites found in plants. They have a polyphenolic nature and exhibit active actions as first line defenses against invading pathogens. Several studies have demonstrated the multiple activities of tannins, highlighting their effectiveness as broad-spectrum antimicrobial agents. Tannins have reported as antibacterial, antifungal, and antiviral compounds by preventing enzymatic activities and inhibiting the synthesis of nucleic acids. Additionally, tannins primarily strengthen the plant cell wall, making it almost impenetrable to harmful pathogens. Most tannins are synthesized via the phenylpropanoid pathway to become secondary metabolites. Increased uptake of tannins has the potential to provide permanent immunity to subsequent infections by strengthening cell walls and producing antimicrobial compounds. Tannins also demonstrate a synergistic response with other defense-related molecules, such as phytoalexins and pathogenesis-related proteins, including antimicrobial peptides. Studying the mechanisms mediated by tannins on pathogen behaviors would be beneficial in stimulating plant defense against pathogens. This understanding could help explain the occurrence of diseases and outbreaks and enable potential mitigation in both natural and agricultural ecosystems.

1. Introduction

Tannins are secondary metabolites synthesized through the phenylpropanoid pathway (Fraga-Corral et al., 2020). Their chemical structure classifies them in to two major types: condensed and hydrolyzable tannins (Bhat et al., 1998; Naumann et al., 2017). Hydrolyzable tannins typically consist of a core esterified with an average of six to ten gallic or ellagic acids esterified with a polyol core (Hartzfeld et al., 2002) while condensed tannins are polymers composed of the flavan-3-ol subunit (Tanner, 2004). However, both types of tannins play a significant role in defending plants against pathogens. Several mechanisms have been reported through which tannins function in plants against pathogens. One of the primary strategies of tannins in plant defense is their direct interaction with microbial structures (Zucker, 1983). Tannins can interfere with the synthesis of cellular systems by binding to certain enzymes, thus regulating secretion. They can also bind to and precipitate proteins (Kumar et al., 2014) and cell wall components of pathogenic bacteria (Kumar et al., 2014). Furthermore, tannins can degrade microbial cell membranes, causing cellular release and ultimately leading to cell death. Furthermore tannins have the capability to bind microbial cells, cell wall proteins, enzymes, and cell membranes inhibiting physiological processes and restricting proliferation and development. Moreover, it is reported that the antimicrobial properties of tannins are due to their antioxidant properties (Koleckar et al., 2008). Tannins play a role in scavenging reactive oxygen species (ROS) that are produced in excess when cells are invaded by pathogens. This helps reduce oxidative stress and shield the cells from deleterious effects. The protective mechanisms of action by tannins are important in plant pathogen interactions, due to the excessive production of ROS during the plants response to the pathogen (Barrett et al., 2018). Moreover, tannins can

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function as signaling molecules, prompting the activation of genes that are responsible for defense mechanisms and systemic acquired resistance. The majority of plants enhance resistance against pathogens after the initial infection. A significant intake of tannins can lead to lifelong resistance to infection by reinforcing the structure of cell walls and producing antimicrobial compounds. Tannins also exhibit a synergistic effect with other defense related molecules such as phytoalexins, and pathogenesis-related proteins, including antimicrobial peptides (Chowdhary et al., 2023). These synergistic interactions increase defense responses and effectively support the plant in combating pathogens. Therefore it is important to understand how tannins interact with other defense-related molecules in order to fully grasp the intricate network of plant defense responses. Tannins not only directly affect microbes, but also play a role in regulating the plant microbiome thereby influencing the relationship between plant and pathogen (Pang et al., 2021). Tannins form symbiotic relationships with beneficial microbes influencing the richness and diversity of the plant microbiome. This primary mechanism enhances the plant's resistance against various pathogens by reinforcing the structure of the cell wall producing antimicrobial compounds, and modulating the plant microbiome. This ultimately increases resilience of plants to diseases. The action of tannins can be influenced by various features, such as environmental conditions, plant genetics, and pathogen pressure (Waterman et al., 2019). Stressors such as drought, heat, or nutrient deprivation can have a significant impact on tannin biosynthesis., This can weaken plants' defense responses (Zhang et al., 2012). Moreover, the buildup of tannins can be influenced by genetic factors specific to certain species or cultivars. These genetic factors, in turn, regulate resistance to diseases. By developing enzymes that degrade tannins or by producing tannin exporter molecules that provide tolerance to these compounds, it is possible to effectively combat resistance against tannins., To achieve this, it is essential to have a comprehensive understanding of pathogen tolerance towards them (Bhat et al., 1998). Tannins serve various roles in plant defense against pathogens, including direct antimicrobial activities, immune responses, synergy with other defense chemicals, and modulation of the plant's microbiome. Furthermore, tannins play a crucial role in various aspects of plant defense (Kolodziej et al., 1999). This review provides a comprehensive exploration of the role of tannins in defense against pathogens and emphasizes their potential applications in agriculture. Enhancing plant resistance against pathogen attacks would be beneficial, and this can be achieved by understanding how tannins activate mechanisms against pathogens. Such understanding could also help reduce the occurrence of disease and outbreaks in both natural and agricultural ecosystems. Therefore, future research should prioritize the exploration of the molecular crosstalk between tannins, plants, and pathogens. This is essential in order to develop innovative and environmentally friendly methods for controlling plant diseases.

2. How tannins affect pathogens with their antimicrobial activity

Many plants contain abundant polyphenolic compounds, including tannins, which are essential for plant defense mechanisms against various abiotic stresses (Waqas et al., 2023), and pathogens (Tsimogiannis et al., 2019). These compounds employ multiple mechanisms to fight against pathogens, including processes that impede the growth and reproduction of pathogens. One specific way in which tannins affect microbes is by causing disruption of the cell membrane (Farha et al., 2020). It has been found that tannins serve as strong binding agents for proteins and components of the membrane wall. However, these substances also have the effect of destabilizing the membrane and increasing its permeability (Tong et al., 2022). Furthermore, this compromises the cells integrity, ultimately leading to its death. Cowan et al. (1999) conducted a study that demonstrated the effectiveness of tannins in fighting bacterial infections by targeting cell membranes. The results of this research provide evidence that tannins have antimicrobial properties (Cowan, 1999). Furthermore, it has been discovered that tannins have the ability to chelate important mineral ions that pathogens require for their growth. This deprives them of the necessary nutrients they need. The chelation of mineral ions negatively affects the enzymatic activities required for the pathogen's metabolism. As a result, it inhibits the pathogens ability to spread. A study conducted by Scalbert et al. (1999) demonstrated the ability of tannins to chelate metal ions, indicating their potential for binding these ions (Scalbert et al., 1999). The results showed that tannins are effective in preventing microbial adhesion to the host (T Morey et al., 2016) and they also play a crucial role in inhibiting colonization. They attach to the microbial surface proteins of microbes, which prevents pathogens from attaching to host tissues. Hagerman et al. (1998) found that tannins can prevent pathogens from sticking together (Hagerman et al., 1998). However, approaches that yield promising and broad-spectrum analytical results are warranted to deeply investigate stress behaviors. For instance, a spatiotemporal mapping of leaf apoplastic ion and metabolite patterns is a valuable approach that enables the simultaneous capture of numerous compounds, including ions, metabolites, proteins, hormones, and others, with a single sampling event. Consequently, it advances the study of the leaf apoplast's roles, such as its function as a refuge for microorganisms, nutrient store, hormone function, cell-cell communication, and conduit for metabolite trafficking (Franzisky, 2023). In summary, tannins perform several functions including the prevention of adhesion, chelation of metal ions, and membrane disruption. These functions work together to protect the host from pathogens.

2.1. Tannins' role against bacterial pathogens

Tannins, which are secondary metabolites found in plants (Anulika et al., 2016), play a crucial role in protecting against bacterial pathogens (Table 1). When plants are exposed to bacterial pathogens, tannins develop impenetrable defense walls. These walls prevent bacterial replication and growth ultimately shielding the plants from bacterial infections. Several researchers have reported the significance of tannins in combatting bacterial pathogens and have discovered their potential applications in agriculture and plant protection (Choi et al., 2020). Investigations have shown the inhibitory properties of tannins against bacterial pathogens. Soufi et al. (2016) examined the antibacterial properties of tannins isolated from the skin of *Punica granatum* against various pathogenic strains (Sufi et al., 2020). The strongly expressed antibacterial effect of tannins on *E. coli* and *Staphylococcus aureus*

Table 1
Tannins' role against bacterial pathogens.

Tannin	Role in Bacterial Stress	Reference
1. Ellagitannins	Inhibit bacterial growth by interfering with bacterial metabolism and cell membrane integrity	Nazzaro et al. (2019)
2. Condensed Tannins	Disrupt bacterial cell membranes and inhibit bacterial growth	Smith et al. (2005)
3. Gallotannins	Exhibits antimicrobial activity by disrupting bacterial cell membranes and inhibiting enzyme activity	Engels et al. (2011)
4. Hydrolysable Tannins	Inhibit bacterial growth by disrupting cell membranes and interfering with bacterial enzyme activity	Smith et al. (2005)
5. Procyanidins	Disrupt bacterial cell membranes and inhibit bacterial adhesion	Dasiman et al. (2022)
6. Prodelphinidins	Inhibit bacterial growth and disrupt bacterial cell membranes	Chew et al. (2020)
7. Phlorotannins	Exhibit antibacterial activity by disrupting bacterial cell membranes	Shannon et al. (2016)
8. Punicalagins	Inhibit bacterial growth and disrupt bacterial cell membranes	Álvarez-Martínez et al. (2024)
9. Roburins	Inhibit bacterial growth and disrupt bacterial cell membranes	Smeriglio et al. (2017)
10. Sericins	Exhibit antibacterial activity by disrupting bacterial cell membranes	Xue et al. (2016)

suggest that these compounds could potentially serve as natural antibacterial agents in plant defense mechanisms (González-Lamothe et al., 2009). Furthermore, the researchers identified the significant impact of tannins on the relationship between plants and bacteria and their role particularly, in the formation of the rhizosphere. The investigation conducted by Badri et al. (2013) revealed that plant roots secrete tannins that inhibit pathogens (Badri et al., 2013). This effect consequently contributes to overall stronger plant resistance against pathogens. Additionally, the significance of utilizing tannins in bacterial infection management has been reported. The activity of hydrolyzable tannin, specifically tannic acid, was studied to suppress bacterial spot disease on tomato plants (Miele et al., 2019) caused by *Xanthomonas* spp (Jones et al., 2004). The results demonstrated that tannic acid inhibits the growth of *Xanthomonas* spp both in vitro and in the plant (Henry et al., 2016). This finding emphasizes the potential of tannins as a substitute for chemical pesticides (Kurhekar, 2016). Tannins play a versatile role in plant protection by exhibiting antibacterial properties and actively contributing to eco-friendly disease management strategies in agriculture (Mal et al., 2021).

2.2. Tannins' role against fungal pathogens

Tannins are a group of secondary metabolites, that are essential for plants to defend themselves against fungal pathogens (Scalbert, 1991). These polyphenolic compounds are closely linked to proteins, enzymes, and cell wall components and inhibit fungal growth and reproduction (Lattanzio, 2013). Several studies have shown that tannins exert antifungal effects through multiple pathways. Therefore, tannins play a significant role in plant defense mechanisms. Tannins directly inhibit fungal growth by disrupting their physiology (Broda, 2020). Raji and Nadi (2023) found the adverse effects of tannins on the phytopathogenic fungus *C. acutatum* (Raji et al., 2023). The tannins isolated from *A. mearnsii* bark showed an antifungal effect. The results showed that the tannins influenced the integrity and ion balance of the fungi's cell membranes, resulting in decreased fungal growth (Elhamouly et al., 2022). Therefore, the direct effects of tannins could potentially act as natural fungicides in plants. Furthermore, tannins induce structural changes in the fungal cell wall, making it more permeable. Silva et al. (2020) conducted a study to examine the antifungal properties of tannins derived from *grape pomace* against the fungus *B. cinerea* (Silva et al., 2020). The results showed that tannins severely altered the fungal hyphae (Chen et al., 2022) and the structure of their cell walls. Therefore, tannins destabilize the fungal cell structure to prevent pathogenic development. Additionally, tannins elevate plant defense responses by inducing signaling pathways and antimicrobial compounds (Pratyusha, 2022). Gao et al. (2020) observed the up-regulation of defense-related genes in cucumber plants in response to *F. oxysporom* (Gao et al., 2020). However, the up-regulation of defense-related genes in cucumber was responsible for the accumulation of tannic acid. Consequently, tannic acid enhances defense against fungi in plants. Several researchers have reported its significant role in plant protection against fungi. Therefore, researchers suggest its application in plant protection strategies.

2.3. Tannins function against viral pathogens

Tannins are a prominent class of secondary metabolites found in plants that exhibit various biological activities, including antiviral properties. Although many studies have investigated the antibacterial and antifungal roles of tannins, several studies have also demonstrated their efficacy against viral pathogens in plants. However, tannins employ a mechanism by which they inhibit viral entry and replication in plant cells. These metabolites bind to the surface of the virus and prevent its attachment to the host cell. Inhibition can also occur through the disruption of viral RNA synthesis or the expression of viral proteins (Montenegro-Landívar et al., 2021). Furthermore, Yang et al. (2019) conducted an experiment and observed that tobacco mosaic virus infection was inhibited by tannins derived from green tea (Yang et al., 2019). Tannins also exert antiviral effects by enhancing plant immunity against viruses. Thakur et al. (2017) also examined the upregulation of defense-related genes by tannins in response to cucumber mosaic virus infection (Thakur, 2017). A mechanism known as mimicking plays a significant function in the defense system. Tannins have the capability to inhibit the invasion of viruses and boost the plants ability to resist them. However, tannins antioxidant properties enable them to exhibit an antiviral effect on the cells of plants by decreasing oxidative stress (Akbari et al., 2022). Furthermore, it was difficult for the virus to survive in plants with reduced oxidative stress. Naik et al. (2023) conducted research in which they infected plants with tomato yellow leaf curl virus and treated them with tannic acid. The results showed that the treatment caused changes in oxidative stress levels (Naik et al., 2023). This treatment increases plant resistance against viruses by blocking their action and entry. Furthermore, tannic acid possesses antioxidant properties that contribute to the efficacy of antiviral activity in plant cells. In conclusion, tannic acid boosts the host system's defense against viruses and exhibits antiviral effects.

2.4. Tannins role against insects

Tannins, are highly abundant in different plant tissues and are vital to the plant's defense mechanism against insects (Table 2). However, tannins play an essential role in plants' natural defense against insect pests and pathogens by restricting the frequency of attacks. Researchers examined the various mechanisms by which tannins defend plants against insects (War et al., 2012). Tannins directly act as an antimicrobial agent, contributing to plants' defense against insect pathogens. Aswad et al. (2022) reported the bioactivity of tannins isolated from urtica weed leaves, bean hull, black tea, and green tea against larvae of cotton leafworm *Spodoptera littoralis* (Boisduval), adults of rice weevil and houseflies using the fumigation technique. The results indicated that tannins show potential for insect control. According to the report, the tannin compound significantly slowed down the growth of these pathogens and limited their ability to infect and destroy plants. Tannin compounds can indirectly limit the potential of insects by reducing their spread due to the deterrence of insect feeding. Another study by Barbehenn and Constabel (2011) reported that tannins reduce the performance of gypsy moth larvae (*Lymantria dispar*) (Barbehenn et al., 2011). Furthermore, the accumulation of tannins in the diet led to a decrease in larval growth, development, and eventually their survival (Schultz, 1989). Thus, tannins limited the external transmission of insect

Table 2
Tannins' role against insects.

Tannin	Role in Insect	Reference
Quercetin	Inhibitory effects on insect growth and development	Cui et al. (2019)
Catechins	Disruption of insect digestive enzymes	Rocchetti et al. (2024)
Ellagic Acid	Larvicidal and ovicidal activity against certain insect species	Adeosun et al. (2016)
Gallic Acid	Repellent and antifeedant properties against insect pests	Oulebsir-Mohandkaci et al. (2018)
Procyanidins	Inhibition of insect feeding and oviposition	Harborne et al. (2017)
Epicatechin	Growth inhibitory effects on certain insect species	Abou-Zaid et al. (1993)
Catechin	Disruption of insect hormonal regulation	Rocchetti et al. (2024)
Punicalagins	Antifeedant and toxic effects on insect pests	Saad et al. (2021)
Myricetin	Repellent and antifeedant activity against insect pests	Su et al. (2018)
Kaempferol	Disruption of insect feeding behavior and growth	Simmonds (2003)

pathogens through the larvae in the plant. Tannins assist in the formation of physical barriers within plants, restricting insect penetration and pathogen colonization. Furthermore, Barbehenn et al. (2006) conducted research on tannins' role in enhancing the resistance of hybrid poplar trees *P. tremula* × *P. xalba* against insect herbivory and pest colonization (Barbehenn et al., 2006). The report showed that hybrid poplar trees increased the accumulation of condensed tannins in their leaves when insects fed on them, which resulted in the hardening of the leaf tissue. As a result, the leaves became resistant to infestation by insects and pest pathogens (Kleiner et al., 2003). Therefore, tannins play a critical role in plant defense against pathogens by acting as antimicrobial agents, limiting insect feeding, and forming physical barriers. Moreover, tannins have the potential to be utilized in agricultural applications for the purpose of assisting in insect and pest control (El-Aswad et al., 2023). However, reducing the agricultural environmental footprint and promoting global sustainability demands the use of organically approved pesticides (Waqas et al., 2024). In this vein, further exploration of tannin-related pesticides could be a potent approach.

3. Conclusion

Tannins are vital for plant defense mechanisms against pathogens due to their antibacterial, antiviral, and fungicidal properties. Tannins inhibit pathogen proliferation by attaching to microbial proteins and disrupting their cell membranes. Furthermore, tannins enhance the plant's resilience against biotic threats, which can be assessed by its overall health and productivity. Investigations of this type of secondary plant metabolites are discussed as a key step in understanding the mechanisms of plant immunity. Additionally, they aid in formulating natural alternatives to synthetic pesticides. Further research is required to investigate the interaction between tannins and pathogens to assess their compatibility with sustainable farming practices. In the future, researcher should focus on clarifying the exact mechanism by which of tannins act as an antimicrobial substance. Additionally, it is important to explore the practical applications of tannins effects in crop protection. Furthermore, gaining a more comprehensive knowledge of the various tannin structures and their specific effectiveness against different pathogens would be beneficial for creating customized applications that are suitable for specific local agroclimatic conditions. Moreover, the inclusion of tannin-rich plant materials in contemporary plant breeding programs will result in the enhancement of natural resistance levels. The utilization of tannins' antimicrobial activity could lead to the establishment of a new agricultural system with minimal or no reliance on chemical applications, thereby promotingantimicrobial activity of tannins can be used to develop a new agricultural system that reduces or eliminates the need for chemical applications. This would have significant benefits for global health and environmental preservation.

Ethical statement

This manuscript work did not involves the use of human subjects.

CRediT authorship contribution statement

Madiha Zaynab: Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Abou-Zaid, M.M., et al., 1993. The effect of one flavone, two catechins and four flavonols on mortality and growth of the European corn borer (Ostrinia nubilalis Hubner). Biochem. Systemat. Ecol. 21 (4), 415–420.
Adeosun, C., et al., 2016. Essential oil from the stem bark of Casuarina equisetifolia exhibits mosquitocidal potential. Journal of Phytopathology & Pest Management 3 (3).
Akbari, B., et al., 2022. The role of plant-derived natural antioxidants in reduction of oxidative stress. Biofactors 48 (3), 611–633.
Álvarez-Martínez, F.J., et al., 2024. Plant-Derived Natural Products for the Treatment of Bacterial Infections. Springer.
Anulika, N.P., et al., 2016. The chemistry of natural product: plant secondary metabolites. Int. J. Technol. Enhanc. Emerg. Eng. Res 4 (8), 1–9.
Badri, D.V., et al., 2013. Application of natural blends of phytochemicals derived from the root exudates of Arabidopsis to the soil reveal that phenolic-related compounds predominantly modulate the soil microbiome. J. Biol. Chem. 288 (7), 4502–4512.
Barbehenn, R.V., et al., 2006. Tannin composition affects the oxidative activities of tree leaves. J. Chem. Ecol. 32, 2235–2251.
Barbehenn, R.V., Constabel, C.P., 2011. Tannins in plant–herbivore interactions. Phytochemistry 72 (13), 1551–1565.
Barrett, A.H., Farhadi, N.F., Smith, T.J., 2018. Slowing starch digestion and inhibiting digestive enzyme activity using plant flavanols/tannins—a review of efficacy and mechanisms. Lwt 87, 394–399.
Bhat, T.K., Singh, B., Sharma, O.P., 1998. Microbial degradation of tannins–a current perspective. Biodegradation 9 (5), 343–357.
Broda, M., 2020. Natural compounds for wood protection against fungi—a review. Molecules 25 (15), 3538.
Chen, W., Xia, S., Xiao, C., 2022. Complex coacervation microcapsules by tannic acid crosslinking prolong the antifungal activity of cinnamaldehyde against Aspergillus brasiliensis. Food Biosci. 47, 101686.
Chew, Y.-L., Goh, J.-K., Arasi, C., 2020. Investigation on antibacterial activity of pyrogallol in methicillin resistant Staphylococcus aureus. Curr. Trends Biotechnol. Pharm. 14 (5), 176–180.
Choi, J., Kim, W.K., 2020. Dietary application of tannins as a potential mitigation strategy for current challenges in poultry production: a review. Animals 10 (12), 2389.
Chowdhary, V.A., Tank, J.G., 2023. Biomolecules regulating defense mechanism in plants. Proc. Natl. Acad. Sci. India B Biol. Sci. 93 (1), 17–25.
Cowan, M.M., 1999. Plant products as antimicrobial agents. Clin. Microbiol. Rev. 12 (4), 564–582.
Cui, B., et al., 2019. Quercetin affects the growth and development of the grasshopper Oedaleus asiaticus (Orthoptera: Acrididae). J. Econ. Entomol. 112 (3), 1175–1182.
Dasiman, R., et al., 2022. A review of procyanidin: updates on current bioactivities and potential health benefits. Biointerface Res. Appl. Chem 12 (5), 5918–5940.
El-Aswad, A.F., Aisu, J., Khalifa, M.H., 2023. Biological activity of tannins extracts from processed Camellia sinensis (black and green tea), Vicia faba and Urtica dioica and Allium cepa essential oil on three economic insects. J. Plant Dis. Prot. 130 (3), 495–508.
Elhamouly, N.A., et al., 2022. The hidden power of secondary metabolites in plant-fungi interactions and sustainable phytoremediation. Front. Plant Sci. 13, 1044896.
Engels, C., Schieber, A., Gänzle, M.G., 2011. Inhibitory spectra and modes of antimicrobial action of gallotannins from mango kernels (Mangifera indica L.). Appl. Environ. Microbiol. 77 (7), 2215–2223.
Farha, A.K., et al., 2020. Tannins as an alternative to antibiotics. Food Biosci. 38, 100751.
Fraga-Corral, M., et al., 2020. Technological application of tannin-based extracts. Molecules 25 (3), 614.
Franzisky, B.L., et al., 2023. In planta exploitation of leaf apoplastic compounds: a window of opportunity for spatiotemporal studies of apoplastic metabolites. In: hormones and physiology. https://doi.org/10.1101/2023.04.05.5355530000000. bioRxiv doi:
Gao, X., et al., 2020. Cucumber Fusarium wilt resistance induced by intercropping with celery differs from that induced by the cucumber genotype and is related to sulfur-containing allelochemicals. Sci. Hortic. 271, 109475.
González-Lamothe, R., et al., 2009. Plant antimicrobial agents and their effects on plant and human pathogens. Int. J. Mol. Sci. 10 (8), 3400–3419.
Hagerman, A.E., et al., 1998. High molecular weight plant polyphenolics (tannins) as biological antioxidants. J. Agric. Food Chem. 46 (5), 1887–1892.
Harborne, J.B., Grayer, R.J., 2017. Flavonoids and insects. In: The Flavonoids Advances in Research since 1986. Routledge, pp. 589–618.
Hartzfeld, P.W., et al., 2002. Determination of hydrolyzable tannins (gallotannins and ellagitannins) after reaction with potassium iodate. J. Agric. Food Chem. 50 (7), 1785–1790.
Henry, P.M., et al., 2016. Inhibition of Xanthomonas fragariae, causative agent of angular leaf spot of strawberry, through iron deprivation. Front. Microbiol. 7, 1589.
Jones, J.B., et al., 2004. Reclassification of the xanthomonads associated with bacterial spot disease of tomato and pepper. Syst. Appl. Microbiol. 27 (6), 755–762.

Kleiner, K.W., et al., 2003. Leaf ontogeny influences leaf phenolics and the efficacy of genetically expressed Bacillus thuringiensis cry1A (a) d-endotoxin in hybrid poplar against gypsy moth. J. Chem. Ecol. 29, 2585–2602.
Koleckar, V., et al., 2008. Condensed and hydrolysable tannins as antioxidants influencing the health. Mini Rev. Med. Chem. 8 (5), 436–447.
Kolodziej, H., et al., 1999. *Enhancement of antimicrobial activity of tannins and related compounds by immune modulatory effects.* Plant Polyphenols 2: chemistry, Biology. Pharmacology, Ecology 575–594.
Kumar, K., Chaudhary, L., Kumar, S., 2014. Exploitation of tannins to modulate rumen ecosystem and ruminants performance: a review. Indian J. Anim. Sci. 84 (6), 609–618.
Kurhekar, J.V., 2016. Tannins-antimicrobial chemical components. International Journal of Technology and Science 9 (3), 5–9.
Lattanzio, V., 2013. Phenolic compounds: introduction 50. Nat. Prod 1543–1580.
Mal, S., Pal, D., 2021. Tannins and polyphenols extracted from natural plants and their versatile application. Bioactive Natural Products for Pharmaceutical Applications 715–757.
Miele, S., et al., 2019. Hydrolysable tannins in agriculture. Tannins-structural Properties, Biological Properties and Current Knowledge, p. 79.
Montenegro-Landívar, M.F., et al., 2021. Polyphenols and their potential role to fight viral diseases: an overview. Sci. Total Environ. 801, 149719.
Naik, B., et al., 2023. Genomics, proteomics, and metabolomics approaches to improve abiotic stress tolerance in tomato plant. Int. J. Mol. Sci. 24 (3), 3025.
Naumann, H.D., et al., 2017. The role of condensed tannins in ruminant animal production: advances, limitations and future directions. Rev. Bras. Zootec. 46, 929–949.
Nazzaro, F., et al., 2019. Effect of polyphenols on microbial cell-cell communications. In: Quorum Sensing. Elsevier, pp. 195–223.
Oulebsir-Mohandkaci, H., et al., 2018. Comparative study of the toxicity of phenolic compounds of coriander (Coriandrum sativum) and false fennel (Aneth graveolens) on Galleria mellonella (Lepidoptera, Pyralidae). Euro-Mediterranean Journal for Environmental Integration 3 (1), 30.
Pang, Z., et al., 2021. Linking plant secondary metabolites and plant microbiomes: a review. Front. Plant Sci. 12, 621276.
Pratyusha, S., 2022. Phenolic compounds in the plant development and defense: an overview. Plant stress physiology-perspectives in agriculture 125–140.
Raji, Y., et al., 2023. Eco-friendly extraction of flavonoids dyes from moroccan (Reseda luteola L.), wool dyeing, and antibacterial effectiveness. Fibers Polym. 24 (3), 1051–1065.
Rocchetti, G., et al., 2024. Impact of in vitro gastrointestinal digestion on the phenolic bioaccessibility and bioactive properties of insect-containing beef burgers. Antioxidants 13 (3), 365.
Saad, A.M., et al., 2021. Polyphenolic extracts from pomegranate and watermelon wastes as substrate to fabricate sustainable silver nanoparticles with larvicidal effect against Spodoptera littoralis. Saudi J. Biol. Sci. 28 (10), 5674–5683.
Scalbert, A., 1991. Antimicrobial properties of tannins. Phytochemistry 30 (12), 3875–3883.
Scalbert, A., et al., 1999. *Polyphenols, metal ion complexation and biological consequences.* Plant Polyphenols 2: chemistry, Biology. Pharmacology, Ecology 545–554.
Schultz, J.C., 1989. Tannin-insect interactions. In: Chemistry and Significance of Condensed Tannins. Springer, pp. 417–433.
Shannon, E., Abu-Ghannam, N., 2016. Antibacterial derivatives of marine algae: an overview of pharmacological mechanisms and applications. Mar. Drugs 14 (4), 81.
Silva, V., et al., 2020. Comparative insight upon chitosan solution and chitosan nanoparticles application on the phenolic content, antioxidant and antimicrobial activities of individual grape components of Sousão variety. Antioxidants 9 (2), 178.
Simmonds, M.S., 2003. Flavonoid–insect interactions: recent advances in our knowledge. Phytochemistry 64 (1), 21–30.
Smeriglio, A., et al., 2017. Proanthocyanidins and hydrolysable tannins: occurrence, dietary intake and pharmacological effects. Br. J. Pharmacol. 174 (11), 1244–1262.
Smith, A.H., Zoetendal, E., Mackie, R.I., 2005. Bacterial mechanisms to overcome inhibitory effects of dietary tannins. Microb. Ecol. 50, 197–205.
Su, Q., et al., 2018. Effect of plant secondary metabolites on common cutworm, Spodoptera litura (Lepidoptera: Noctuidae). Entomol. Res. 48 (1), 18–26.
Sufi, D., Sunday, E., Mustapha, T., 2020. Antibacterial effect of Acacia nilotica and Acacia senegalensis fruit extracts on Escherichia coli and Salmonella typhi. FUTY Journal of the Environment 14 (2), 1–8.
T Morey, A., et al., 2016. Antifungal activity of condensed tannins from Stryphnodendron adstringens: effect on Candida tropicalis growth and adhesion properties. Curr. Pharmaceut. Biotechnol. 17 (4), 365–375.
Tanner, G., 2004. *Condensed tannins.* Plant pigments and their manipulation. Ann. Plant Rev 14, 150–184.
Thakur, A., 2017. Evaluation of Biological Control Strategies against a Range of Plant Pathogens.
Tong, Z., et al., 2022. Biological function of plant tannin and its application in animal health. Front. Vet. Sci. 8, 803657.
Tsimogiannis, D., Oreopoulou, V., 2019. Classification of phenolic compounds in plants. In: Polyphenols in Plants. Elsevier, pp. 263–284.
Waqas, M., et al., 2023. Short-term phosphorus deficiency induces flavonoid accumulation in the lamina of pak choi: a finishing treatment that influences inner quality. Sci. Hortic. 314, 111953.
Waqas, M., Yaning, C., Desneux, N., 2024. Pesticide reduction: clustering organic croplands. Trends Ecol. Evol. https://doi.org/10.1016/j.tree.2024.04.011.
War, A.R., et al., 2012. Mechanisms of plant defense against insect herbivores. Plant Signal. Behav. 7 (10), 1306–1320.
Waterman, P.G., Mole, S., 2019. Extrinsic factors influencing production of secondary metabolites in plants. In: Insect-plant Interactions. CRC press, pp. 107–134.
Xue, R., et al., 2016. Shape changes and interaction mechanism of Escherichia coli cells treated with sericin and use of a sericin-based hydrogel for wound healing. Appl. Environ. Microbiol. 82 (15), 4663–4672.
Yang, Y., Zhang, T., 2019. Antimicrobial activities of tea polyphenol on phytopathogens: a review. Molecules 24 (4), 816.
Zhang, L.H., et al., 2012. Effects of fertilization and drought stress on tannin biosynthesis of Casuarina equisetifolia seedlings branchlets. Acta Physiol. Plant. 34, 1639–1649.
Zucker, W.V., 1983. Tannins: does structure determine function? An ecological perspective. Am. Nat. 121 (3), 335–365.